Comparison of Path Rank Ordering Schemes for Structure-Borne Noise

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Abstract

This research examines two rank ordering methods for structure-borne noise transmission paths. One method is the conventional path disconnect comparison (PDC) that is often used because of its simplicity. However, the boundary conditions may change as one or more paths are disconnected. On the other hand, transfer path analysis (TPA) is a method that decomposes the contributions of each path in terms of partial sound pressures. In order to compare these two systems, a simple experimental system was developed. The system consists of two metal plates: a thicker source plate and a thinner receiver plate. The top plate has a higher natural frequency and fewer modes while the bottom plate has a lower natural frequency and more modes. This is similar to a real structure, like a vehicle, where noise is a consideration. The plates in the experimental system are connected by three paths in a diagonal arrangement. The connecting paths can either be steel or plastic. This allows for eight distinct configurations of three paths when paths of similar geometry are considered. In order to ensure a valid model, the acceleration frequency response function results were compared between the finite element model and the experimental measurements. Once the model was validated, finite element and boundary element software were used to measure the path contributions in the PDC method and the TPA method. The results from both methods were tabulated and compared.

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I would like to thank Dr. Raj Singh for allowing me the chance to work on this research and for his help in development of the idea and analyzing data. I would also like to thank Akira Inoue for his previous research that provided the basis for my work and for his help in teaching me how to use the software. I would like acknowledge the Center for Automotive Research for allowing me to use their facility. Finally, I would like to thank the Honda partnership for their generous support of the project.

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List of symbols and abbreviations

$\lvert A_z/F_z \rvert$	Accelerance, type of transfer function, magnitude (s^2/m)
a(ω)	Acceleration amplitude as a function of frequency (N-m/s^2)
BEM	Boundary Element Method
FEM	Finite Element Method
FRF	Frequency Response Function
F(ω)	Force amplitude as a function of frequency (N)
IL	Insertion Loss (dB)
NVH	Noise, Vibration and Harshness
P	Plastic
PDC	Path Disconnect Comparison
P(ω)	Pressure amplitude as a function of frequency (Pa)
S	Steel
SPL	Sound Pressure Level (dB)
TPA	Transfer Path Analysis
α	Alpha scheme for the Path Disconnect (connecting only one path)
β	Beta scheme for the Path Disconnect (disconnecting a single path)
ω	Frequency (rad/s)

1. Introduction

In any structure with sub-assemblies, noise is transmitted to the observer through multiple, parallel paths [1]. In a vehicle, for example, noise is transmitted from the engine to the driver through structural connections and each of the engine mounts. Because it is desirable to make the vehicles and other structures as quiet as possible, it is important to be able to quantify the dominant paths of transmission. Consumers often associate quietness with quality. Noise and vibration concerns in structures are annoying to the user and can cause permanent hearing damage if the level is high enough. In order to reduce the noise, it is first necessary to be able to understand the source of the noise and how the noise is transmitted through the structure. Understanding the transmission then allows for countermeasures to be put into place. These countermeasures in a vehicle can include hardware modifications, modification of the stiffness of connections, or addition of a tuned vibration absorber [2].

The research will evaluate the results from two methods for quantifying the contribution from each path: path disconnect comparison (PDC) and transfer path analysis (TPA). A simplified linear, time invariant source-path-receiver system will be considered. Path disconnect comparison has been used for generations in industry. It is straightforward and intuitively easier to comprehend than TPA. In PDC, one path or all paths except one path are disconnected. The change in the overall noise level due to disconnecting the path is measured and used to rank the path dominance [3]. Transfer path analysis is a more recently developed process and is a more data intensive process than PDC. Transfer path analysis requires measurement of many frequency response functions (FRFs) [2]. In order complete TPA experimentally, the data acquisition system needs to have many channels to ensure consistent results for the system and a lot of data must be stored. The advantage of the TPA is that no paths are removed during measurement. This means that the dynamic interactions of the paths are not changed during the measurement. This, in theory, should lead to more precise measurements of the path dominance. The differences between PDC and TPA are summarized in Table 1.

Table 1: Summary of Differences between PDC and TPA

Path Disconnect Method	Transfer Path Analysis
• More Straight forward method • Only requires basic data acquisition equipment (microphone and data acquisition system) • Requires being able to remove path • Changes the dynamic interactions of the paths	• More complicated • Time Consuming • Requires extensive hardware and software • Requires removal of the source • Quantifies the dominant paths of noise transmission without modifying the operational state of the system.

2. Objectives

The main objectives of this work are the following:

- Verify experimentally the Finite Element Model acceleration response in terms of frequency
- Compare path rank orders by PDC and TPA in terms of the sound pressure level
- Discuss validity of each system

In order to evaluate the two methods of measuring path dominance, a simplified experimental system was fabricated and modeled using Finite Element software. The validity of the model was verified by correlating experimental and theoretical results. This allowed the model to be used to theoretically evaluate the path dominance using the TPA and PDC methods. The results were compared for the two methods.

3. Background

a. Structural Noise Transmission

When looking at the contribution of each path in a structure, it must noted that contributions of each path can either increase the overall noise level or reduce the overall noise level by canceling out noise. One way to think about this is considering the contribution from each path as a vector. The vector has both a direction and a magnitude. This idea is illustrated in Figure 1. The solid red vector is the overall contribution and the dotted green and blue vectors are the contributions of individual paths. The overall contribution, the red vector, is the same in both cases. The magnitude of the green vector is much greater in the triangle on the right. However, in the triangle on the right, the blue vector has a canceling effect with the green vector. Although both sets of vectors yield the same overall level, this cannot be found by adding the magnitudes of the contributing vectors. This is similar to the noise contribution of individual paths in structures. The given path may either increase or decrease the noise level. The magnitudes of the noise level cannot be summed to get the correct overall noise level. This principle is important to understand in any sound pressure measurements.

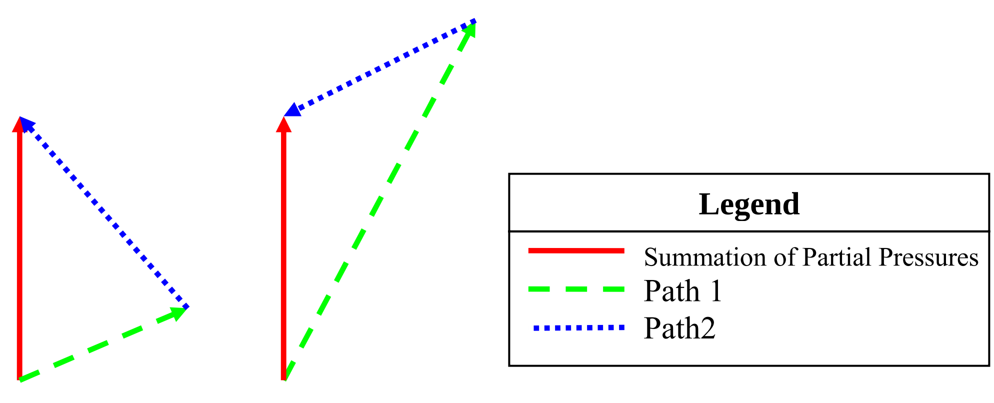

Figure 1: Illustration of Path Contribution in a Structure at any Frequency

b. Experimental System

In order to investigate PDC and TPA, the experimental system shown in Figure 2 was used. The system consists of two pieces of sheet metal. The top sheet, the source plate, is 0.25 inches thick. The bottom plate, the receiver plate, is 0.125 inches thick. This is similar to a typical structures where the source has fewer modes than the receiver over a given frequency range. The two plates are connected by steel or plastic paths. The paths are held in place by screwing them into the plates. As shown in the figure, there are five possible locations for the paths to be connected to. For this paper, the paths will be in a diagonal configuration across the plate. The paths will all be 0.25 inches in diameter and 6.0 inches in length. The experimental system was also modeled using an experimentally verified, finite element modeling (FEM). All the TPA work was done using the finite element model while the work for the PDC was done using both experimental data and results from the finite element model.

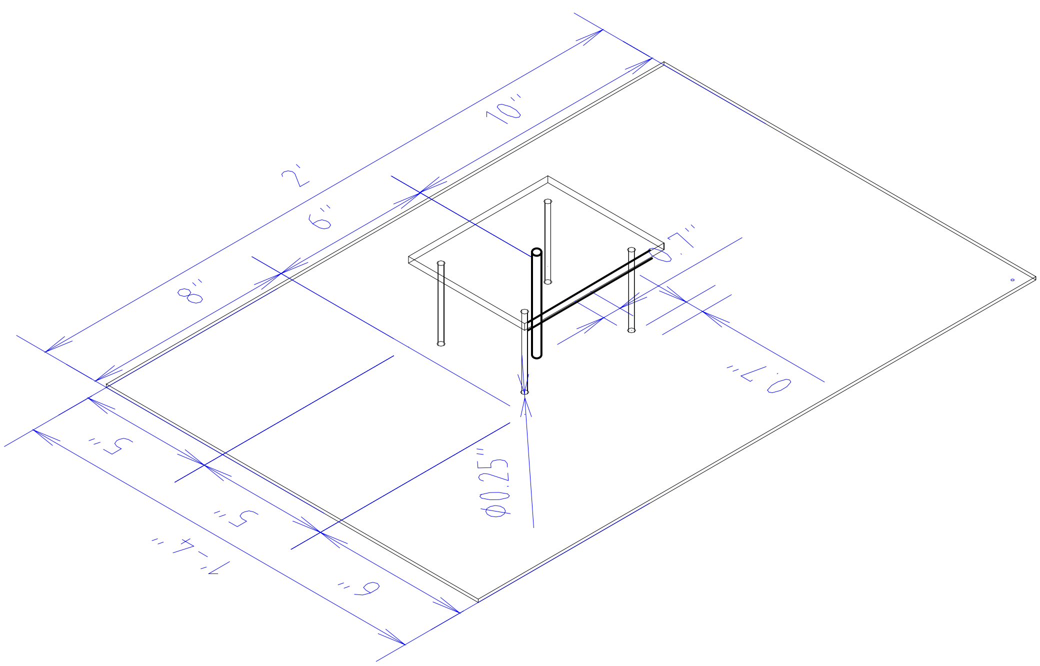

Figure 2: Dimensions of Experimental System (only three paths were used in this work)

4. Verifying the Finite Element Model

The experimental system was modeled using finite element modeling software. A dynamic signal analyzer was used to obtain the experimental FRFs of the system. The pressure and acceleration FRFs were taken in a hemi-anechoic chamber and the experimental setup is shown in Figure 3. Given in Table 2 is the complete list of experimental equipment used in this setup. Piezo-Electric accelerometers were placed at the point of the impact (referred to as driver point) and at the bottom left corner of the plate (referred to as source point). The driver point and receiver point are shown in Figure 4. These points were chosen because of the free-free boundary conditions on the corner. The accelerometers were attached using beeswax. The wax attaches the accelerometer to the plate but still allows the accelerometer to read the correct measurement over a large frequency range and does not damage the accelerometers. The top plate was impacted using the impact hammer.

In order to ensure consistent results, five measurements were made and the average was taken. Coherence was measured across all the measurements which is a measure of the consistency of the runs. The closer the coherence is to one, the more consistent the results. Sample plots of coherence are shown in Figure 5 and Figure 6. If the signal at a given frequency is low, it is difficult to obtain good coherence which accounts for the drops in coherence. However, where the signal is low, the poor coherence is not a great concern. FRFs were measured in the x-direction, y-direction, and z-direction (vertical). However, because the plate was impacted in the vertical direction, the z-direction results for the FRFs are much greater than the y-direction and x-direction. This work will evaluate only the z-direction for the PDC method and for the

TPA method. Future work could look at the effect that the x and y-direction accelerations have in the FRF measurements.

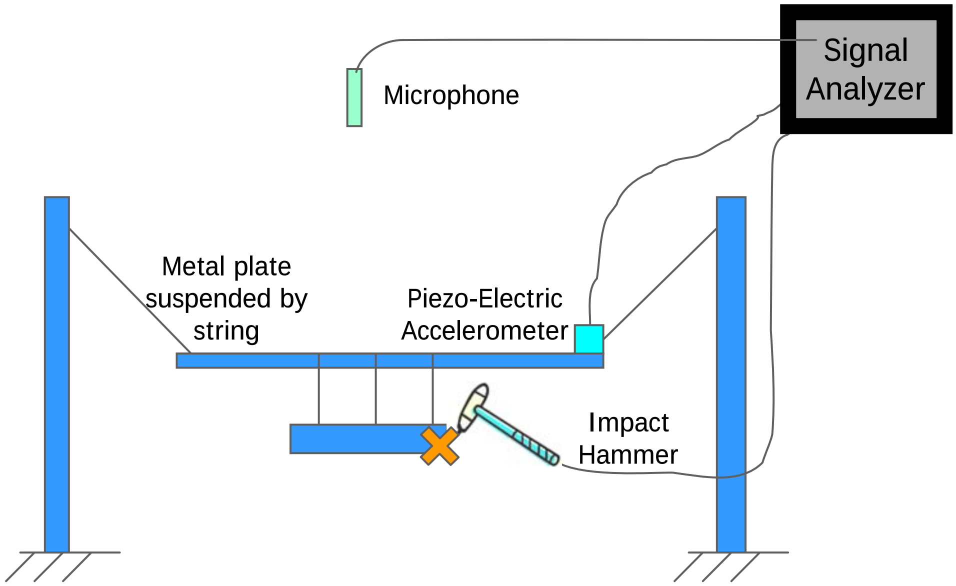

Figure 3: Experimental Setup for Anechoic Chamber

Table 2: Table of Insturmentation

Equipment	**Manufacturer**	**Website**	**Model and Specifications**
Microphone	PCB	<www.pcb.com>	ICP Microphone, Model 130D20
Impact Hammer	PCB	<www.pcb.com>	Modally Tuned Impact Hammer, Model 086B03
Signal Analyzer	Hewlett Packard	<www.hp.com>	35670A Dynamic Signal Processor
Accelerometer	PCB	<www.pcb.com>	PCB Shear Accelerometer, Model 356A15

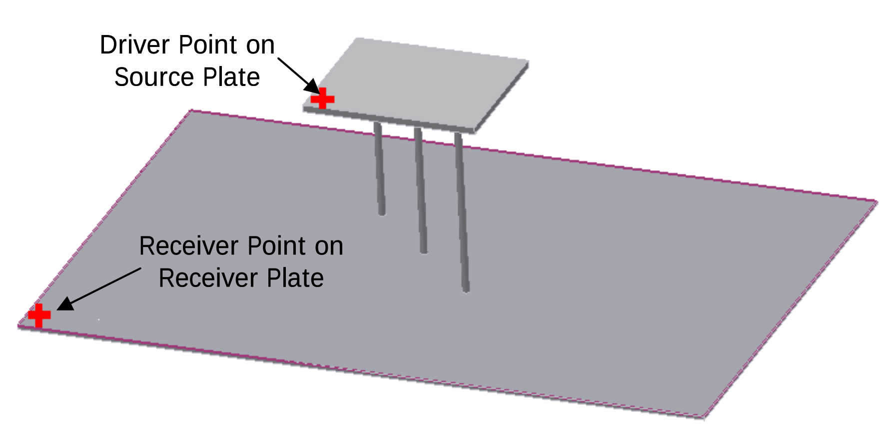

Figure 4: Experimental System showing the Driver Point and the Receiver Point for accelerance measurements

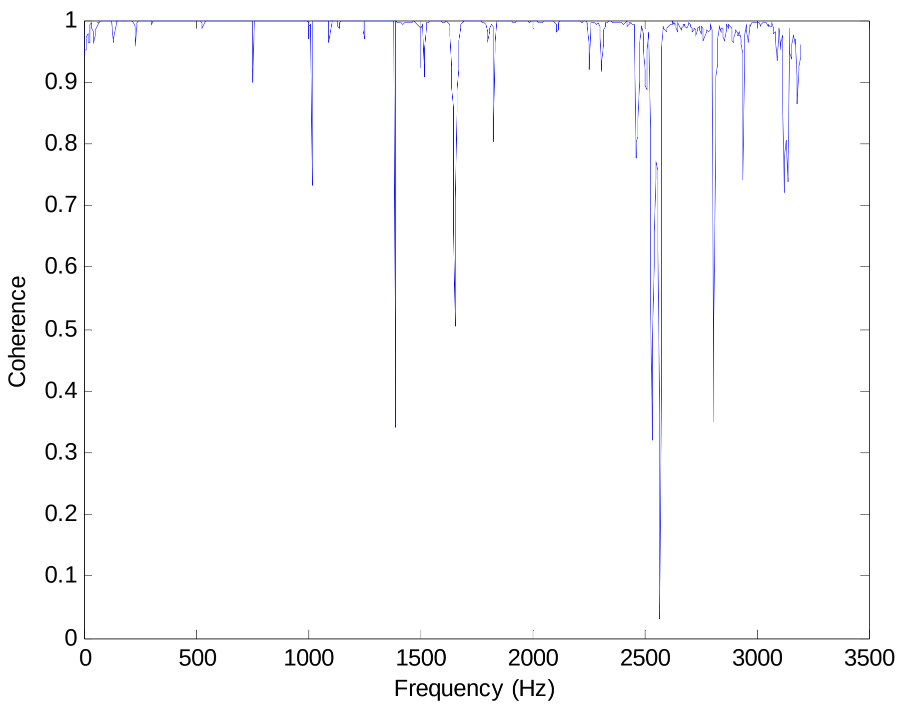

Figure 5: FRF Coherence for 3 Long, Thin Steel Paths for Accelerance

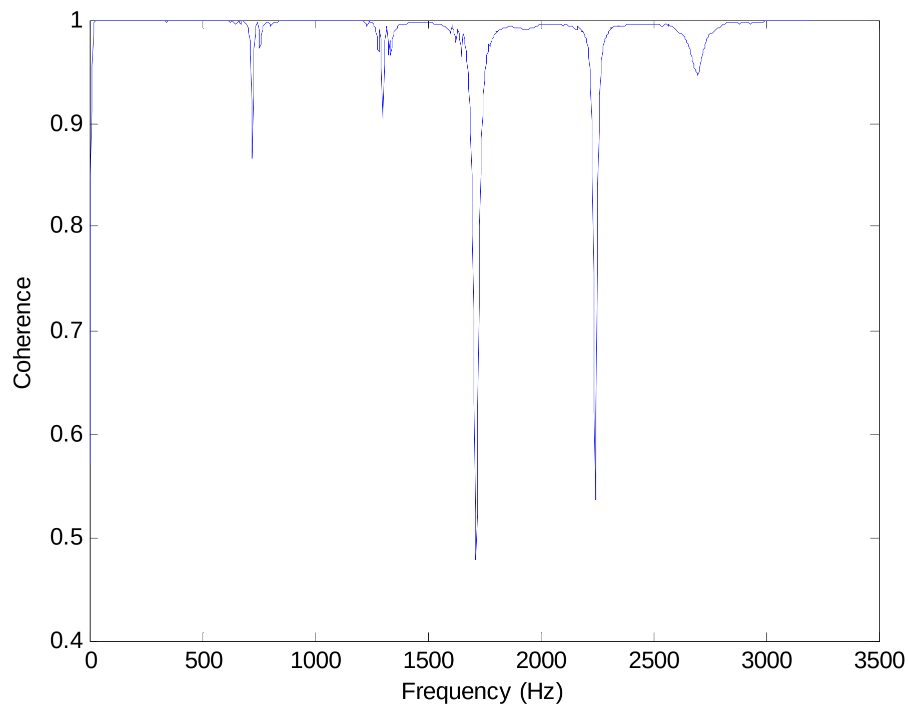

Figure 6: FRF Coherence for 3 Long, Thin Plastic Paths for Accelerance

These results from the experimental measurements were compared with the FEM model. The material properties and mesh properties are given in

Table 3. The experimental and theoretical results were plotted on the same plot. The x-axis is frequency and a range of 0 to 1000 Hz was used as this is a range over which the acoustic output is typically highest. The y-axis is accelerance which is the measure of acceleration output to force input. This is in units of meters per second squared over Newtons ($m/(s^2\text{-}N)$). As shown in Figure 7 and Figure 8, the model and experimental results match well when taking a measurement at either the driving point or the receiver point. Figure 9 and Figure 10 show good correlation for the plastic paths as well. Finally, Figure 11 and Figure 12 demonstrate the model is effective for mixed paths of plastic and steel.

Table 3: Material Properties for FEM Models

Property	Steel	Plastic
Modulus of Elasticity	180 GPa	5 GPa
Poisson's Ratio	0.3	0.45
Density	7900 kg/m^3	2400 kg/m^3
Damping	0.3 %	0.3%

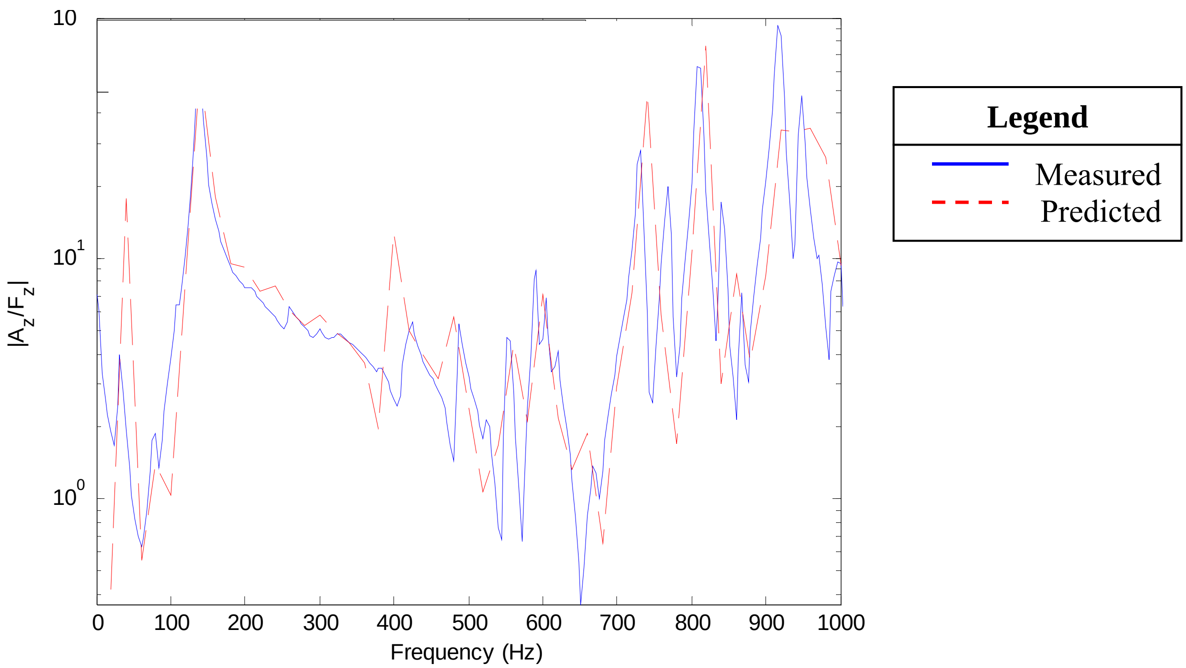

Figure 7: FRF at the Driving Point for Three Long, Thin Steel Paths

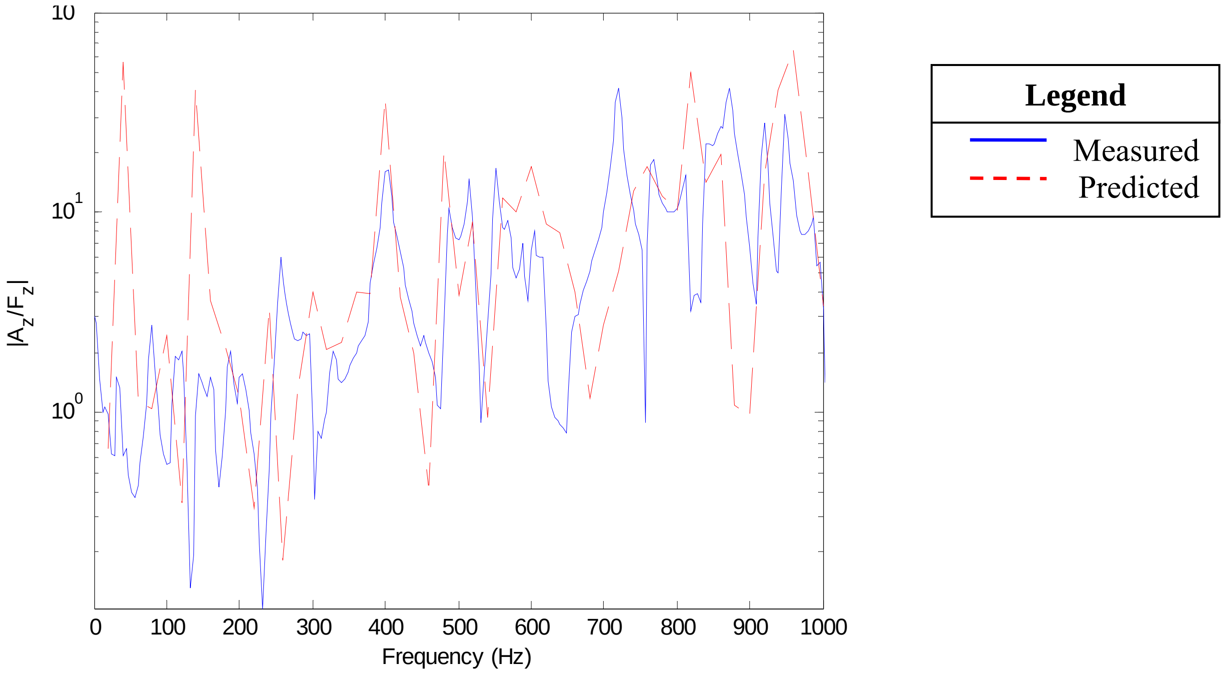

Figure 8: FRF at Receiver Point for Three Long, Thin Steel Paths

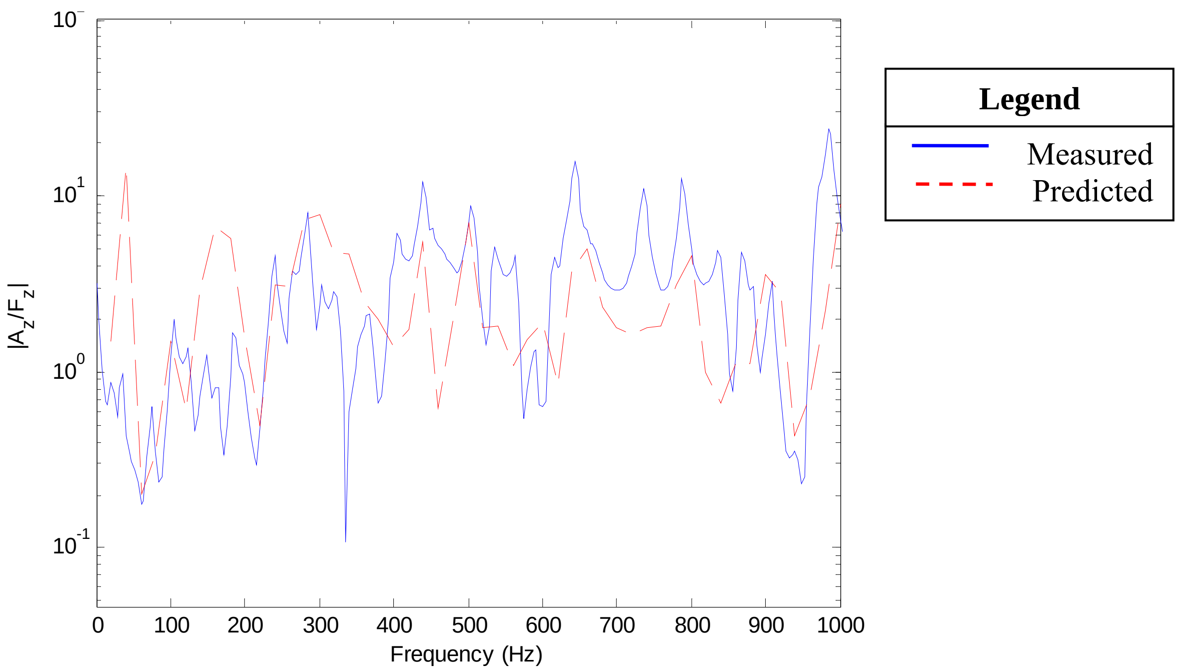

Figure 9: FRF at the Driving Point for Three Plastic Paths

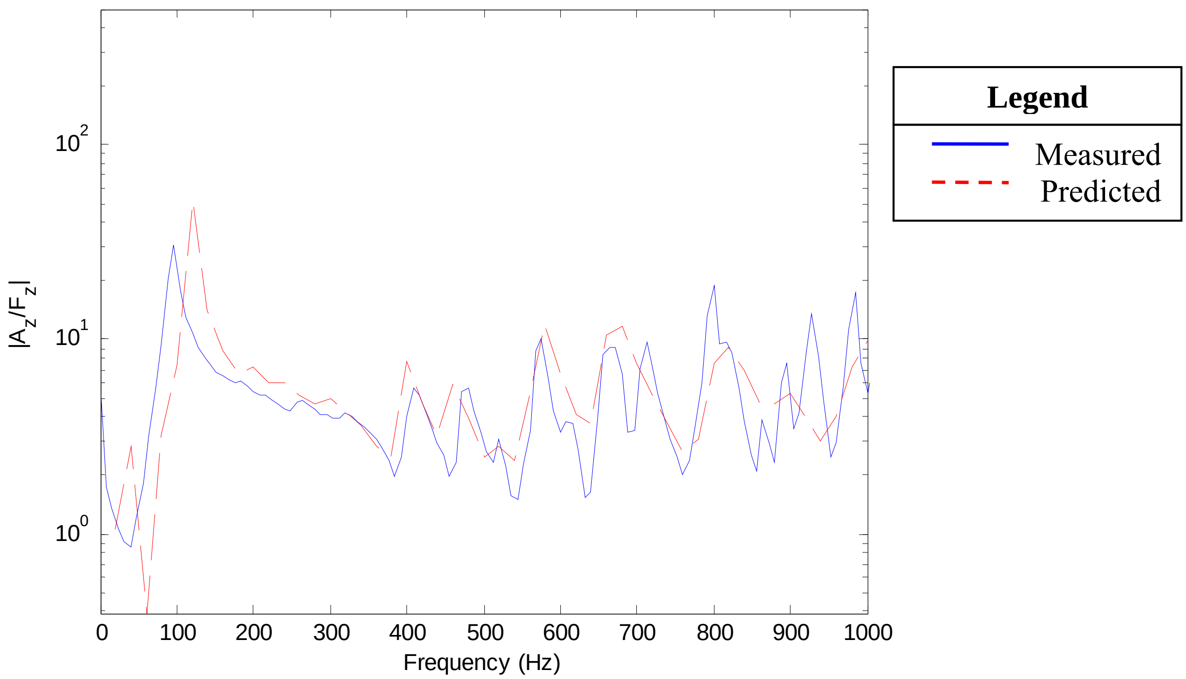

Figure 10: FRF at the Receiver Point for Three Plastic Paths

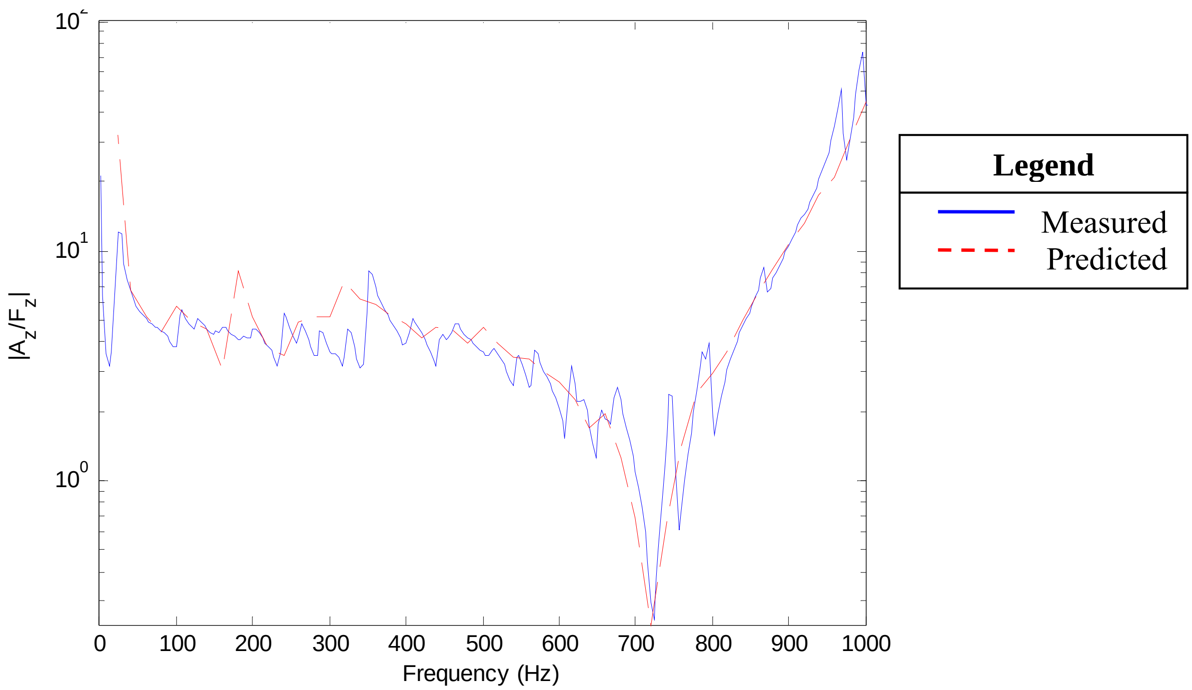

Figure 11: FRF at Driving Point for Steel, Plastic, and Steel Paths

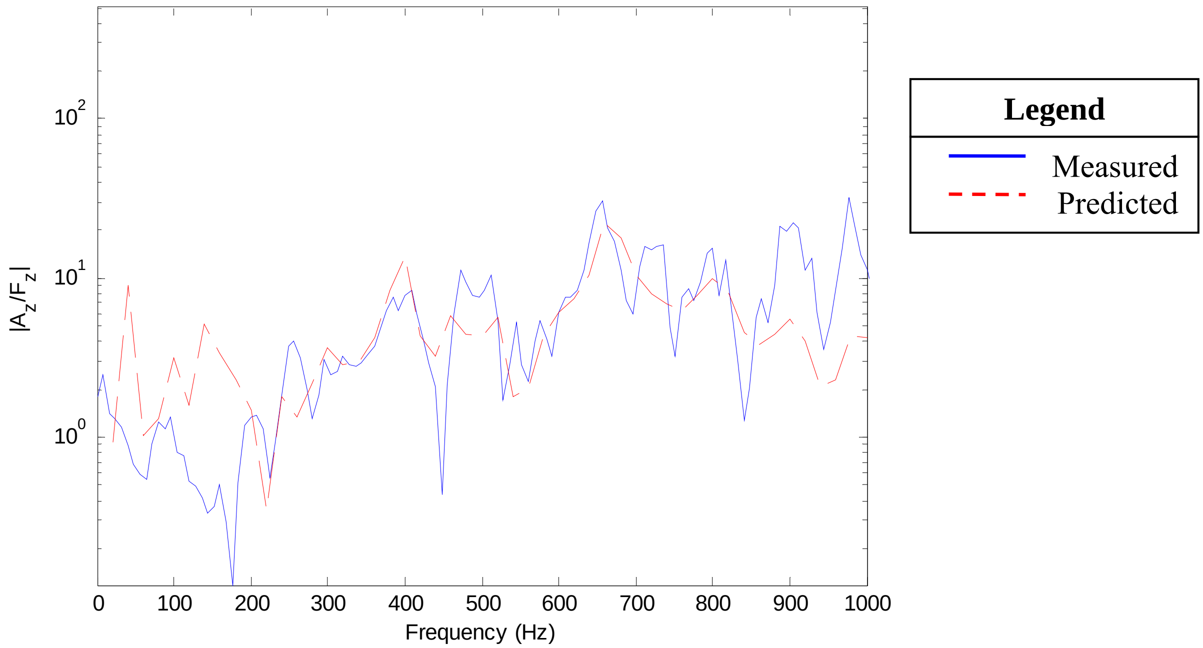

Figure 12: FRF at Receiver Point for Steel, Plastic, and Steel Paths

From these graphs, it can be seen that overall, the correlation is good. In general, the driving point for the model shows better correlation than the receiver point. This is expected as the driver point acceleration is measured much closer to the source of the force. While the measured and predicted accelerances were not identical, they did show that the amplitude were at least of the same magnitude. In the finite element model, the paths were modeled as being simply two dimensional lines which was a good assumption since the paths were only 0.25 inches in diameter. However, to achieve better model and experimental correlation, the paths could be modeled as three-dimensional objects to account for the moments and forces caused by a three-dimensional object. This would be especially important if looking at paths of a greater diameter. Since this research focuses on the thin paths, it was concluded that this model is accurate enough and will provide valid data for evaluating the TPA and PDC methods.

5. Sound Pressure Using Path Disconnect Comparison

Path disconnect comparison is straight forward and has commonly been used to identify dominant paths. All the analysis for the PDC will use Finite Element Model (FEM) software and Boundary Element Software (BEM). Additionally, a numerical computing program will be used for results analysis and plotting. The summary of software used is given in Table 4.

Table 4: List of Software Used

Purpose	Software	Website
Finite Element Modeling	ANSYS	<www.ansys.com>
Boundary Element Modeling (Vibro-Acoustic Analysis)	SYSNOISE	<www.lmsintl.com/sysnoise>
Computation and plotting	MATLAB	<www.mathworks.com>

For this paper, five combinations of paths will be considered as shown in Table 5. The paths are configured as shown in Figure 13. The figure shows the view of the source plate from the top of the system. The diagonal configuration with three paths was chosen because no previous work had been done on the experimental system using the diagonal configuration. Additionally, the diagonal configuration allows for the output from Path 1 and Path 3 to be compared which is significant because Path 1 and Path 3 and both located symmetrically at the corners of the plate. The main difference between the two paths is their location relative to the point of impact as Path 1 is located closer to the impact point than Path 3.

Table 5: Summary of Path Combinations

Path 1	Path 2	Path 3	Path Configuration Abbreviation
Steel	Steel	Steel	SSS
Steel	Steel	Plastic	SSP
Steel	Plastic	Steel	SPS
Steel	Plastic	Plastic	SPP
Plastic	Plastic	Plastic	PPP

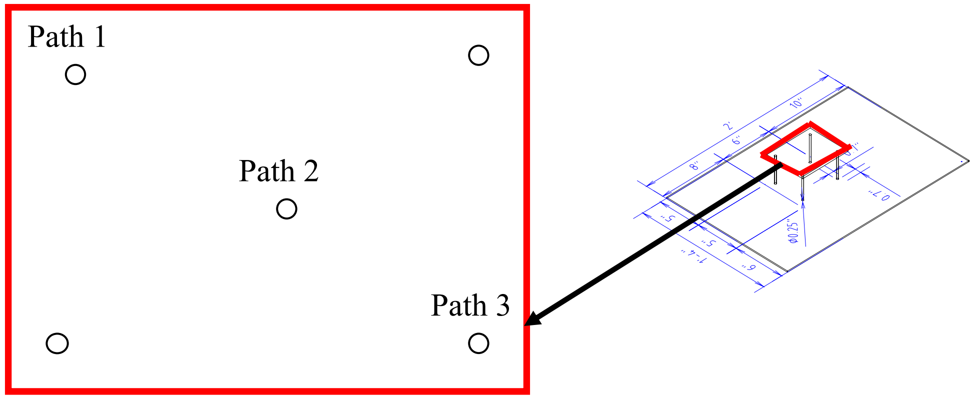

Figure 13: Top View of Source Plate Showing Path Locations

This research will look at two schemes for PDC when taking experimental results. The first, called the Alpha Scheme, is where all the paths are disconnected except for one path. In this case, the greater the overall sound pressure level (SPL) after disconnecting a given path, the more dominant the disconnected path. The Alpha Scheme is illustrated in Figure 14. The Beta Scheme levels all the paths connected except for one. In this case, the greater the reduction in noise level from disconnecting a given path, the more dominant the path. This is illustrated in Figure 15. In experimental work, the Alpha scheme is not always possible since the source cannot always be supported by a single path. For instance, an engine could not be supported by a single engine mount.

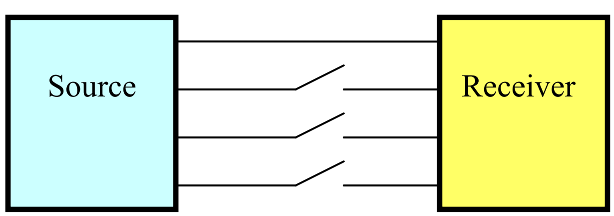

Figure 14: Alpha Scheme for Path Analysis (one path connected at a time)

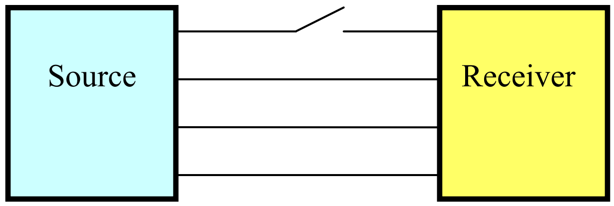

Figure 15: Beta Scheme for Path Analysis (one path disconnected at a time)

To quantify the effect of a given path for the PDC method, Insertion Loss (IL) is calculated [1]. Insertion Loss is defined as follows:

$$IL = 10 \cdot \log\left(\frac{SP_i^{\,2}}{P_{ref}^{\,2}}\right) - 10 \cdot \log\left(\frac{SP_d^{\,2}}{P_{ref}^{\,2}}\right) \tag{4.1}$$

Where the variables are defined as follows:

SP_i = RMS Sound Pressure (Pa) measured with all paths connected

SP_r =RMS Sound Pressure (Pa) with all paths except one disconnected (Alpha scheme) or with only one path disconnected (Beta scheme).

P_{ref}= Reference Pressure equal to 20 μPa

The insertion loss is measured in deciBels (dB). In the Alpha scheme, a low IL indicates a more dominant path; the difference between having all the paths connected and only that path connected is small. In the Beta scheme, a high IL indicates a less dominant path; disconnecting that single path reduces the overall sound pressure level significantly. To find the SPLs, the FEM software and BEM software packages were used. For the calculations, only 6.0 inch paths with a diameter of 0.25 inches were used. In order to accomplish this, the FEM code was run to create a velocity profile of the plate for a configuration with all the paths connected. Then the BEM software was used to find the acoustic pressure for this configuration. The sound pressure level was simulated as being measured from 24.0 inches underneath the middle of the longer side of the receiver plate as shown in
Figure 16. This distance is far enough away to avoid microphones that anomalies of high or low sound pressures.

For the path disconnect comparison, the given three-path configuration was run using the velocity profile from the FEM software to get the velocity profile for the plate. Velocity profiles were also obtained with either a single path connecting the two plates (Alpha) or with a single path disconnected (Beta). Each FEM result file was used to find the pressure at the point below the plate in the BEM software.

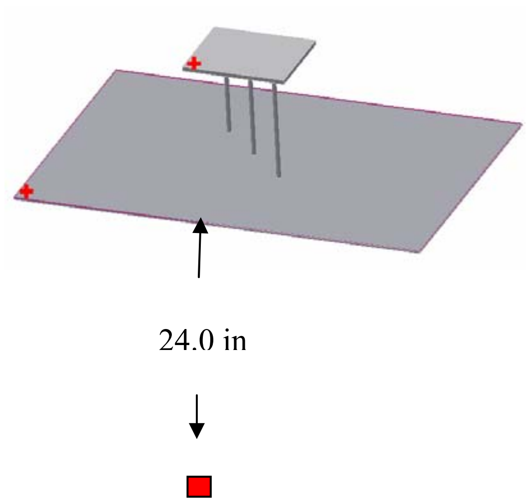

Figure 16: Location of Sound Pressure Measurement

The results from the PDC Alpha scheme are given in

Table **6**. The Beta scheme results are given in Table 7.

Table 6: Summary of Insertion Losses for Alpha Scheme (lower IL= dominant path)

Alpha	SSS			SSP			SPS			SPP			PPP		
Path Number	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Overall	1.0	0.5	1.0	6.3	4.6	5.1	8.4	8.1	8.4	2.6	1.1	1.5	2.2	0.7	2.3
0-200 Hz	4.3	-3.4	3.3	7.0	-0.7	5.9	7.0	-0.2	5.9	6.6	-0.6	5.6	4.3	-2.9	3.6
200-400 Hz	2.2	3.9	6.3	4.2	4.5	6.9	7.7	9.0	11.9	4.9	4.7	7.6	3.6	3.4	0.5
400-600 Hz	-0.3	2.5	-0.6	3.6	4.8	1.7	10.5	12.8	10.3	-1.8	-1.2	-3.7	1.3	1.9	2.1
600-800 Hz	-0.8	-0.6	-2.1	4.8	3.6	2.2	8.7	9.6	7.5	-2.2	-2.7	-4.8	0.6	0.0	1.8
800-1000 Hz	-0.3	-0.3	-1.5	11.6	10.1	8.9	8.1	9.1	6.9	5.5	5.0	2.8	1.2	0.7	3.7

Table 7: Summary of Insertion Losses for Beta Scheme (higher IL= dominant path)

Beta	SSS			SSP			SPS			SPP			PPP		
Path Number	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Overall	-2.7	-7.1	-4.1	1.3	2.0	0.5	7.1	0.4	5.9	0.1	-1.7	0.4	2.4	3.8	1.8
0-200 Hz	-2.6	-2.5	-2.1	0.1	-0.5	0.7	2.8	0.1	1.2	2.4	-0.9	2.3	2.9	0.5	2.9
200-400 Hz	4.0	-6.9	0.5	4.5	-1.5	-1.7	12.0	-1.4	12.6	7.7	-0.7	1.3	3.6	9.8	4.6
400-600 Hz	-2.1	-10.9	-1.6	0.2	1.6	-0.6	9.6	0.0	12.9	-4.4	-3.8	-3.1	1.6	4.9	1.5
600-800 Hz	-4.4	-7.8	-4.7	-0.1	3.2	1.2	6.2	1.8	3.7	-6.2	-3.8	-2.8	1.3	1.7	0.0
800-1000 Hz	-8.3	-7.2	-12.6	2.1	6.8	3.0	5.3	1.2	-0.7	1.1	0.7	4.3	2.3	2.0	0.2

In many of the experiments, a smaller IL was found. Although it is difficult to quantify what level of IL is too low to consider significant, all the data should be evaluated with the fact that some error in the measurement. The main source of error is the inability to create a perfect model of the system, especially since the steel and plastic have different damping properties. Additionally, the materials were assumed to be linear. This may not be the case, especially for the plastic paths. Error is also is inherent in the PDC process as the interfacial conditions are being changed which can shift the natural frequencies and modes of the system.

6. Sound Pressure using Transfer Path Analysis

Another way to rank the path dominance is by transfer path analysis [4]. TPA results are based on measuring the vector contribution of each path. In experimental TPA, FRFs between the receiver and a system input are measured. The typical input for vibro-acoustic transfer functions is a force using an impact hammer or shaker [2]. The output at the receiver is usually typically measured using accelerometers in multiple locations of the receiver. For each accelerometer, operational data and the stiffness of the connections must be known. Ideally, the source side is disconnected from the receiver when measuring to FRFs to prevent backflow of vibration through the plate. This is one of the major difficulties with TPA since in practical systems, disconnecting the source and receiver can be difficult or impossible. In cars, for instance, measurement of the FRF for analyzing the engine as a source requires removing the engine from the car. This is a time consuming process. However, if more accurate results are provided, TPA can save significant amounts of time in terms of trouble shooting noise, vibration and harshness issues in vehicles.

The basic equation for TPA states that the acceleration for the as function of frequency is the sum of accelerance times force for each path. This equation is given below:

$$a(\omega) = \sum_{i=1}^{\#Paths} \frac{a(\omega)}{F_i(\omega)} \cdot F_i(\omega) \tag{5.1}$$

$a(\omega) =$ Receiver Acceleration Spectrum as a function of frequency

$\frac{a(\omega)}{F_i(\omega)} =$ Accelerance = Transfer Function between the receiver and the input force at path i

$F_i(\omega) =$ Force Spectrum at transfer path i

$\frac{a(\omega)}{F_i(\omega)} F_i(\omega) =$ Partial Acceleration

When the acceleration in a given path is higher, more noise is transmitted by that path. The acceleration for the system is found by summing all the partial accelerations. The accelerance is simply a ratio of the acceleration in a path for a given force in that path. As mentioned earlier, the accelerance should be measured without the source connected to prevent flow of energy back through the source. In this way, the contribution of a single path can be isolated.

One of the biggest issues with TPA is that it requires that the force be predicted in each path. In experimental systems, it is difficult to measure the force in situ. One way to do this is to measure the accelerations of the source-path-receiver system. Then measure the acceleration for a given force input for the path-receiver system. By taking the inverse of the acceleration to force transfer function and multiplying by the input force, the force in the path can be predicted [4]. Additional, methods for indirect force prediction are given in the paper by Inoue et al [5]. For our study, the finite element model will be used to predict the forces seen in each path. However, in an experimental system, the force prediction is more complex.

In this study, the TPA is done theoretically using Finite Element Method (FEM) Software and Boundary Element Method (BEM) Software. The advantage of using software to complete theoretical TPA is that is allows for flexibility in modifying the system. This is especially important in the design stages of a structure such as a vehicle. The disadvantage is that in order to complete the TPA, an accurate model of the system must be developed. This is difficult in vehicles because of their complex acoustic interactions between many noise sources. However, if creation of a model is possible, theoretical TPA allows for flexibility in design and gives an understanding of how to modify the system to minimize the acoustic output for a given point.

Theoretical TPA is similar to experimental transfer path analysis but different quantities are measured. In theoretical transfer path analysis, the pressure-force transfer function is measured instead of the accelerance. The calculation of the transfer function is given as follows:

$$P(\omega) = \sum_{i=1}^{\#Paths} \frac{P(\omega)}{F_i(\omega)} \cdot F_i(\omega) \tag{5.2}$$

$P(\omega)$ = Total sound pressure as a function of frequency

$F_{i,z}(\omega)$ = Force spectrum in vertical direction at transfer path i, measured with the source plate

$\dfrac{P(\omega)}{F_{i,z}(\omega)}$ = Transfer function between the sound pressure output and the input vertical force at path i, measured with no source plate

Similar to Equation 5.1, Equation 5.2 calculates the partial contribution of each path to the total output for the system. In the case of Equation 5.2, it is the partial pressure contribution of each path instead of partial acceleration. The transfer function between the sound pressure output and in the input force is measured with the source removed. For the system in this study, this term was found by applying a unit force at each path in the vertical direction.

For the three path system for this research, the equation is as follows:

$$P_{total}(\omega) = \frac{P(\omega)}{F_{1,z}(\omega)} F_{1,z}(\omega) + \frac{P(\omega)}{F_{2,z}(\omega)} F_{2,z}(\omega) + \frac{P(\omega)}{F_{3,z}(\omega)} F_{3,z}(\omega) \tag{5.3}$$

The partial pressures show the dominance of each path. All the values are in the frequency domain and assume the system is time invariant. Another way to think of this is illustrated in Figure 17. The whole block represents the total pressure. The total pressure is made up of the contribution from each path.

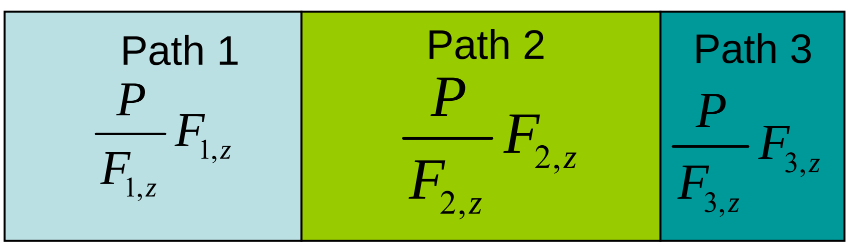

Figure 17: Visual Illustration of Partial Pressure

The partial pressures from the TPA method for the SSP system are shown in Figure 20. Each line represents the partial pressure from a different path. It can be seen from the figure that the path dominance is frequency dependent. The amplitudes of the output are generally similar for all the paths. However, the most dominant path is not the same for the entire frequency range. Figure 21 shows the comparison of the indirect and direct measurement of the total pressure. This is meaningful because it verifies that the direct and indirect measurements of the total pressure are similar. These trends were seen for all the data configurations.

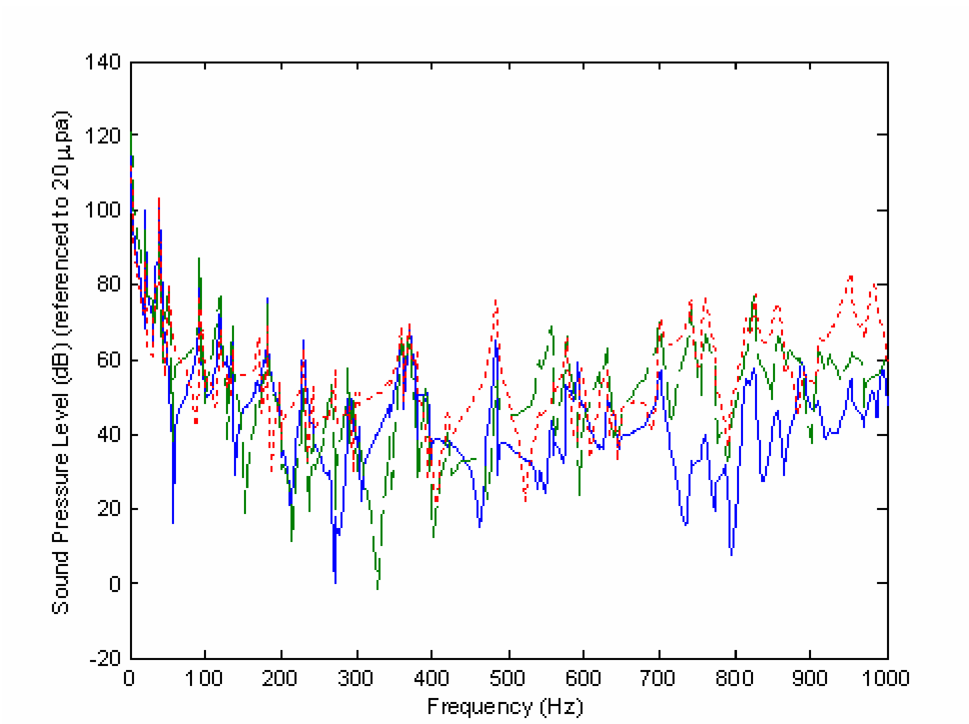

Figure 18: Sound Pressure Contribution from Paths in SSP system, '—' is path 1, '--' is path 2, and '···' is path 3.

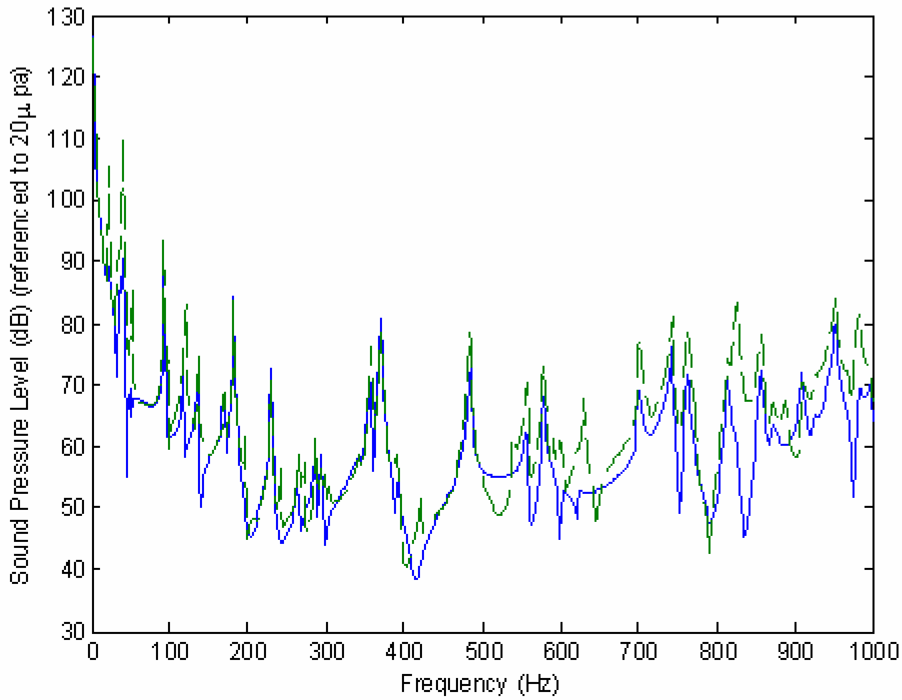

Figure 19: Total Sound Pressure Level for the SSP System from the Summation of Partial Pressure and using BEM Software Directly, '—' is direct from BEM Software and '--' is the summation of the partial pressures

7. Comparison of Methods

The two methods for evaluating path dominance now can be evaluated. Table 7Table 8 gives a comparison of the methods for the 200-400 Hz frequency range. The yellow boxes indicate the dominant path. The values for the non-dominant path are found for TPA by subtracting the partial sound pressure for the dominant path from that for the non-dominant path. For the PDC, the insertion losses are compared. For the Alpha scheme, the lower the IL indicates a more dominant the path. To find the value for the table, the non-dominant path IL is subtracted from the IL for the dominant path (lowest IL). The beta scheme is similar to the TPA in that the higher IL indicates a more dominant path. For this, the IL for the dominant path is subtracted from that of the non-dominant path. Essentially, the table quantifies how many dB less dominant a given path is relative to the dominant path.

Table 8: 200-400 Hz Comparison of Path Ranking

Path Number	Steel, Steel, Steel SSS			Steel, Steel, Plastic SSP			Steel, Plastic, Steel SPS			Steel, Plastic, Plastic SPP			Plastic, Plastic, Plastic PPP		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
TPA	0.0	-0.8	-1.6	0.0	-0.6	-1.5	0.0	-1.1	-2.2	0.0	-3.0	-3.9	0.0	-0.1	-1.8
Alpha Scheme	0.0	-1.7	-4.2	0.0	-0.3	-2.7	0.0	-1.3	-4.2	-0.2	0.0	-2.9	-3.1	-3.0	0.0
Beta Scheme	0.0	-10.9	-3.4	0.0	-6.0	-6.2	-0.6	-14.0	0.0	0.0	-8.5	-6.5	-6.2	0.0	-5.2

Table 9: Comparison of Path Ranking up to 1000 Hz

Path Number	Steel, Steel, Steel SSS			Steel, Steel, Plastic SSP			Steel, Plastic, Steel SPS			Steel, Plastic, Plastic SPP			Plastic, Plastic, Plastic PPP		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
TPA	-3.0	-1.5	0.0	-3.6	-2.0	0.0	-2.6	-1.7	0.0	-2.0	-1.7	0.0	-3.0	-0.3	0.0
Alpha Scheme	-0.5	0.0	-0.6	-1.7	0.0	-0.6	-0.3	0.0	-0.3	-1.5	0.0	-0.3	-1.5	0.0	-1.6
Beta Scheme	0.0	-4.3	-1.4	-0.7	0.0	-1.5	0.0	-6.7	-1.2	-0.3	-2.1	0.0	-1.5	0.0	-2.0

From this data, it can be seen that the TPA ranks the same path as dominant over a given frequency range. Although the magnitudes are changed, the dominant path remains the same even when the material or configuration is modified. The results from the Alpha and Beta are similar with many of the differences between a path being dominant or not being less than 1 dB. Due to various sources of errors, these differences could be considered insignificant. The overall results are consistent between the alpha and beta schemes in all regions. TPA results show to be highly location dependent.

8. Conclusions

This research illustrates some of the difficulties encountered with trying to quantify the dominant paths in system. There are no absolute measurements of structural path dominance so it is difficult to determine which methods are correct. In this simulation, the dominant path was the same for all TPA simulations and did not discriminate as to the material. This result is unexpected as the material properties varied greatly between the steel and the plastic. One reason for this could be because the magnitude was considered, not the phase of each of the vectors. In the future, evaluation of the phase of the vectors should be considered. It also shows that in the real world, changing the path material is not necessarily the best solution. The path disconnect results were similar for the alpha scheme and beta scheme. However, the effect of the changing boundary condition must be considered when looking at the path disconnect scheme. Additionally, real world systems often cannot be supported by a single path so the Alpha scheme may not be practical. Further research is required to solve the issues posed in this work.

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